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FIBER-AND INTEGRATED-OPTIC COMMUNICATION TECHNOLOGY

NAVAL ELECTRONICS LABORATORY CENTER

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FIBER- AND INTEGRATED-OPTIC COMMUNICATION TECHNOLOGY

Applications assessment study, investigation of material and device physics, and preliminary cost-benefit analysis indicate areas of definite performance gains and cost savings from use of integrated and fiber optics, particularly in avionics systems.

W. E. Martin and D. J. Albares

Research and Development

24 August 1973

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Material and device physics

PROBLEM

Explore the application of fiber-optic and integrated-optical-circuit (IOC) technology to DoD problem areas in aircraft, shipboard, undersea, and land-based systems. Assess the capability of fiber-optic transmission lines, using both IOCs and discrete sources and detectors, to meet the requirements of electromagnetic interference (EMI) rejection, size, weight, switching, and bandwidth in military systems. Advance the state of the art in material and device physics and techniques in the fabrication and evaluation of IOC components. Establish the feasibility of using fiber-optic and IOC technology for secure (nonradiating), radiation-resistant, and EMI-free, multi-GHz communication systems on military platforms, including ship, aircraft, undersea, and land-based operations.

RESULTS

Applications assessment studies and a preliminary cost-benefit analysis indicate areas of definite performance gains and cost savings from use of fiber-optic/IOC technology, particularly in avionics systems. Progress in fiber optics has made possible the use of conventional off-the-shelf discrete components in existing and proposed systems with immediate applications. Proposed fiber-optic/IOC systems offer size, power, and reliability advantages as well as the capabilities of high-capacity, point-to-point and data-bus-multiplexing systems. Progress has been made in IOC technology, particularly modulators for use in wide-bandwidth systems. Several unique IOC devices have been investigated which promise utilization of the extremely wide bandwidth and information-carrying capability of single-mode fiber-optic waveguides.

RECOMMENDATIONS

1. Develop prototype fiber-optic links for all platforms in DoD applications.
2. Perform research and development in the areas of fiber-optic/IOC systems for high-capacity point-to-point links and data-bus-multiplexing applications.
3. Continue research and development in IOC fabrication techniques, particularly diffusion and IOC-device physics for components such as modulators, waveguide couplers, switches, and input/output couplers.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The fabrication of miniature solid-state optical components and thin-film waveguides to connect them on semiconductor or dielectric substrates is becoming feasible with the advancement of such disciplines as the material sciences, quantum electronics, and guided-wave optics. Integrated optical components — sources, detectors, modulators, and various coupling elements — on one or more tiny substrates will comprise systems much smaller in size and weight than optical systems employing discrete components. The new systems will be much less susceptible to environmental hazards, such as mechanical vibrations, extremes in temperature, and electromagnetic fluctuations, because of their small size and packaging density. In addition, wideband active components, such as waveguide electro-optic modulators, will be able to operate at very low power levels because of the small dimensions involved.

Guided-wave optical components have found an important potential use in the area of optical communications because of the recent progress in the fabrication of single-mode fiber-optic waveguides with very low losses. Fiber-optic waveguides with losses as low as 4 dB/km at 0.85- μ m and 1.06- μ m wavelengths (for GaAs and Nd-YAG lasers, respectively) and with single-mode fibers having anticipated bandwidths as high as 10 GHz for a 1-km length immensely widen the horizon of optical communications. However, devices must be developed to couple energy efficiently with the fibers and to process the optical information efficiently at rates approaching the bandwidth capacity of the fibers.

Integrated optics will perform a number of functions in the area of wide-bandwidth optical communications. They include rapid modulation and switching by guided-wave elements using applied fields to generate small electro-optic or magneto-optic index changes, coupling, filtering of signals, light detection by p-n junctions or other structures in thin films, and light generation by thin-film laser elements.

Fiber-optic-waveguide systems will offer significant advantages for military information transfer, both immediately, with discrete components and multimode fibers, and in the future, with single-mode fibers and integrated optical elements. These advantages include freedom from electromagnetic interference (EMI), elimination of grounding problems, and increased security (no signal leakage), as well as the potential for large size, weight, power consumption, and cost savings. In addition to high-capacity point-to-point communications, a major interest in integrated optics from a military standpoint is the potential for implementing a fiber-optic-transmission-line, multiterminal (data bus) multiplexing system through low-loss coupling and modulation elements. This will provide isolated-terminal, redundant information transfer, thus facilitating the truly modular (including distributed computer) command control and communications system.

The objective of the program reported here is to advance the material and device physics of integrated optics for military applications, to establish in concert with other Navy and DoD programs a continuing assessment of system requirements and cost-benefits for R&D investments in each application area, and to produce prototype optical elements and subsystems that are aimed at satisfying these requirements. The work on the program that was performed at Naval Electronics Laboratory Center (NELC) and on contracts administered by NELC was in the areas of integrated-optical-circuit (IOC) applications assessment, materials for IOC devices and substrates, pattern fabrication, theoretical analysis, components, and system concepts.

Specifically, NELC addressed applications assessment, problems of material and device physics, and the development of novel fabrication techniques for integrated-optic components. Investigations were centered on the fabrication of waveguides and waveguide electro-optic modulators. Hughes Research Laboratories (HRL) performed work in high-precision pattern delineation and fabrication techniques suitable for integrated optical components and systems in glass and polymer films. C. Yeh at the University of California at Los Angeles (UCLA) continued theoretical calculations of the properties of optical waveguides with arbitrary refractive index variations as would be found in physically realizable waveguides. J. H. Harris at the University of Washington addressed the problem of efficient coupling of light and electrical energy into and out of integrated-optic configurations, a critical area of concern for practical IOC realizations. Reference 1 describes the results of this program during the period 1 April 1972 to 30 September 1972. This report covers progress from 1 October 1972 to 31 March 1973, including, in succession, the general areas of applications assessment, cost-benefit analysis, and material and device physics.

APPLICATIONS ASSESSMENT

The emphasis in this program is on applications of fiber-optic-waveguide systems to military information transfer. Present-day fiber-optic communication technology, involving multimode fiber-optic bundles and discrete semiconductor sources (light-emitting diodes, LEDs) and detectors (silicon PIN diodes), received great stimulation and impetus from the announcement in November 1970 by Corning Glass Works of glass-fiber waveguides with 20-dB/km attenuation (commercial-grade fibers had about 1000 dB/km). Since then, military systems applications have been studied and a number of feasibility demonstrations made (ref. 2). These have pointed up dramatic performance and cost advantages for a wide range of potential system applications. The important properties of fiber-optic transmission lines are:

1. EMI and cross-talk immunity
2. Security — no signal leakage
3. No electrical ground problems

4. No short circuits
5. No ringing problems
6. Large bandwidth for size and weight
7. Small size, light weight, flexibility — ease of installation
8. Low cost
9. High temperature tolerance (500 to 1000°C)
10. Safety in combustible areas
11. High tensile strength
12. No copper (strategic material)
13. Potential nuclear-radiation resistance

A major technology development effort to optimize and qualify present fiber-optic components, cables, sources, detectors, and connectors is being planned for the Navy and DoD. The present status of multimode (step index) fibers is shown in table 1. Commercial LEDs and detectors, while not yet adapted or optimized for fiber optics, can be used today. Data rates of commercial LEDs range up to about 40 Mbits/sec.

TABLE 1. PROPERTIES OF FIBER-OPTIC MULTIMODE WAVEGUIDES
(CORNING GLASS WORKS).

Single Fiber		
Loss		2 dB/km (near IR)
Length		>4 km (limit not established)
Data rate (incoherent source)		50 Mbits/sec-km
Tensile strength		120,000 lb/in. ²
Outer diameter		125 μ m (0.005 in.) (not critical)
Minimum bend radius		3 mm
Splice loss (Bell Labs)		0.5 dB
Bundles — PVC Jacket		
Length		330 m (limit not established)
Loss		
Delivered to Navy (NELC)		80 dB/km
Reported		30 dB/km
Splice loss		1.5 dB

Based on considerations of size, cost, power requirements, and reliability, gallium arsenide LED sources and silicon PIN detectors are the choice for use in many present fiber-optic communication applications. After the choice of source and detector has been made, the main tradeoffs involve signal bandwidth, transmission line length, and fiber-optic attenuation factor. Results of a calculation (ref 3) of the maximum fiber-optic attenuation factor (in dB/km at 9000 Å) consistent with a particular length-bandwidth requirement are given in table 2. A signal-to-noise ratio of 30 dB for the

TABLE 2. MAXIMUM FIBER-OPTIC ATTENUATION FACTOR
(IN dB/km) CONSISTENT WITH A PARTICULAR
LENGTH-BANDWIDTH REQUIREMENT.

Bandwidth	Length		
	50m	300m	1000m
4 kHz analog	1100	180	50
5 MHz analog	550	90	25
2 Mbits/sec PCM	800	130	40
10 Mbits/sec PCM	600	100	30
50 Mbits/sec PCM	500	80	20

analog signals and an error rate of 10^{-7} for the digital signals was assumed. According to this table, attenuation factors in the 500-to-1100-dB/km range will be required for aircraft applications (maximum distance: ~50 m) and in the 80-to-180-dB/km range for naval vessels (maximum distance: ~300 m).

The development of IOC's for use with the single-mode, wideband, fiber-optic waveguide will sharply increase the performance capabilities and, hence, the scope of potential military usage. In addition to the general benefits enjoyed by the present-technology fiber-optic systems, the IOC (plus single-mode fiber) systems promise:

1. Smaller size and weight and lower power requirements
2. Efficient frequency (color) multiplexing
3. Very-low-loss (0.5 dB) couplers
4. Multipole switching
5. Greater bandwidth (10 GHz for 1 km)
6. Batch fabrication economy
7. Reliability

Consequently, IOC communication finds anticipated DoD applications in point-to-point links on every platform — aircraft, ship, land, and undersea. These IOC systems could also function with point-to-point multiplexing techniques in time, frequency, or space (one channel per fiber) division. Both analog and digital information, including audio, video, data, radio, radar, and electronic-intercept information, could be handled by IOC systems. Naturally, not all applications will utilize the bandwidth capacity of IOC's; many will capitalize on other features, such as their small size, low power, switching capability, etc.

System applications for general fiber-optic communications are being studied, and the following considerations for the different military platforms have emerged.

AVIONICS APPLICATIONS

The area of avionics data transfer is likely to be the first major beneficiary of fiber-optic technology. Present problems in this area are, naturally, weight and size of wiring, EMI, cross talk, vulnerability, and lack of flexibility of cable harness configurations. These problems are further accentuated in high-performance and surveillance aircraft, such as fighters, VSTOL aircraft, and reconnaissance and antisubmarine aircraft. In these cases, the density of electronic equipment is high, and component-density requirements continue to increase. Such problems are made even more severe by the high cost of wiring and installation, maintenance, and modifications.

Point-to-point applications would certainly be the nearest-term use of fiber optics. There would be advantages in simple one-for-one substitution, but the most effective scheme would be in multiplexing in either time, frequency, or space. A sizable fraction of the present data-handling needs could be accommodated by 10-MHz links less than 100 m long, and most of these requirements can be met today. If point-to-point fiber links with multi-GHz bandwidths were available, they could handle much of the radio, radar, and electronic-intercept data.

An A-7D aircraft containing navigation and weapon-delivery electronic systems has been evaluated for replacement of some 300 point-to-point wire links between systems by approximately 50 fiber-optic lines using a degree of time-division multiplexing. Decreases are estimated in weight and cost upon rewiring of the navigation and weapon-delivery systems in an aircraft of this sort. The total weight would be down by about 30 kgm (70 lb). Although the total parts cost would also be reduced by nearly \$6000, the weight reduction is more significant when one realizes that payload weight penalty costs are \$2000 per kilogram (\$1000 per pound) or more over the life cycle of a high-performance aircraft.

The concept of data-bus multiplexing, which is vital to future avionics systems, will be discussed separately later in this report.

SHIPBOARD APPLICATIONS

Shipboard interior communication has many problems in common with those of aircraft, and, although weight and size are less critical in conventional ships, they are quite important in high-performance surface craft, such as air-cushion ships and hydrofoils. Further, EMI and electromagnetic compatibility within the ship is a serious problem. A number of applications are practical today, such as the transfer of voice, video, and computer data with fiber optics.

An application of fiber optics presently being pursued is secure communications involving command control information. A six-station telephone system using fiber optics is being fabricated for shipboard demonstration and evaluation. Substitution of optical fiber cables eliminates the signal radiation which occurs from all electrical transmission lines and makes such a telephone system more secure. A second demonstration

system for shipboard use will be a closed-circuit TV link using wideband FM and long, low-loss fiber optics. This application will emphasize the EMI immunity and lack of signal radiation of the fibers. Over a year ago, links were developed and engineered for the Precise Time and Time Interval System to distribute clock pulses within a ship or shore station; these await deployment of the total system. Finally, computer data links have been fabricated for use in systems such as the Naval Tactical Data System and the Message Processing Distribution System.

UNDERSEA APPLICATIONS

Undersea fiber-optic applications emphasize the need for medium to very-long lines (some being much in excess of a kilometer) and, therefore, the need for very low losses. In addition to telecommunications, there are potential applications for both towed and stationary acoustic arrays, for tethers to various sensors and submersible vehicles, and for penetrations in submarine hulls. Bandwidths range from a few kHz to tens of MHz.

In the towed array, the size constraints are severe on the cable design. The cables should be as small in diameter as possible to reduce the drag and to ease the deployment problem. Further, there is the need for approximately neutral bouyancy in such a cable. There is also the need for reasonable bandwidth — say, 10 MHz — over the cable length, since, for even the low-frequency data one would get from a hydrophone array, such bandwidths are required for faithful transmission of information. Fiber optics, with its bandwidth and size advantages, can have a major impact on such undersea cables.

Fiber optics can also be utilized undersea for the redesign of the hull penetrators for electrical input-output to a submarine. Typically, there are a large number of feed-throughs in the hull which can have multiple electrical conductors. The desire to minimize the number of holes in the pressure hull leads to consideration of an optical port which would be much smaller than the standard electrical one and possess greater bandwidth. Such a design has successfully undergone pressure tests at 1400 kgm/cm² (20,000 lb/in.²) at the Naval Undersea Center, and should offer additional benefits in reliability.

LAND-BASED APPLICATIONS

Expected land-based uses of fiber optics include both strategic and tactical communications. In addition to long-distance telecommunications requiring maximum bandwidth and minimum attenuation, there are links in which the EMI immunity is crucial, some in which nuclear-radiation resistance is needed, and others in which the absence of signal radiation from the fiber optics is important. Tactical applications would naturally take advantage of weight and size savings in portable systems, and include command control systems for Army and Marine Corps command posts. Typically, these command posts include some dozen or more huts containing communication, radar, data-processing, and display equipment, all of which

would have to be transported by planes, helicopters, trucks, etc. These huts are presently linked together over distances of tens of meters or more with large amounts of copper cables the weight of which, it is estimated, constitutes about half of the total system weight. Application of fiber optics to these point-to-point links with some multiplexing would result in dramatic weight and size savings and eliminate cross talk, ground loops, and EMI. Bandwidth requirements are typically in the 10-MHz range for present systems.

DATA-BUS APPLICATIONS

An application area of major potential impact to DoD is that of the data bus — a single transmission line that carries many different multiplexed signals and serves a number of spatially distributed terminals. In avionics, there are strong trends toward increased microminiaturization (medium-scale integration, MSI, and large-scale integration, LSI), digital processing, and system integration; these naturally point toward data-bus systems that are increasingly evident in the design of new military aircraft, such as the F-14, F-15, and B-1 generations (ref. 4). Although these trends are strongest in avionics systems, they are also growing in the shipboard area, particularly with the advent of high-performance surface craft and advanced ship concepts stressing modularity on both function and construction levels (ref. 5).

These requirements on both shipboard and aircraft platforms naturally imply system-level data-bus multiplexing because of several important properties. The data bus provides a truly modular communication system where, with standard interfaces at the terminals, various electrical subsystems can be plugged in or pulled off. A data-bus system can be less expensive to install and maintain, lighter in weight and smaller in size, more reliable, easier to modify and expand, and less vulnerable to damage than systems based on point-to-point links. For example, it has been shown that multiplexing and system-level data busing on the planned B-1 bomber will result in the elimination of 53 km (33 miles) of wire and a savings of 1000 kgm (2000 lb) in take-off weight (ref. 6).

The realization of practical data-bus systems is largely a result of recent advances in compact and inexpensive multiplexers and demultiplexers. However, inadequacies of the transmission line — generally a coaxial cable in present-day data-bus systems — can limit the number of terminals, bandwidths, reliability, and error immunity of the data bus. Susceptibility to reflections and ringing, cross talk, EMI, ground-level voltage shifts, and fire damage, as well as bandwidth limitations, are shortcomings of coaxial cable which are aggravated by the stringent requirements of the data-bus system. Furthermore, the technology of electrical transmission lines reached maturity decades ago — the coaxial cable of today is not much different from that of 1950 — and there is little chance of major improvement in this area.

The fiber-optic transmission line is a strong candidate to replace electrical lines in data-bus systems of the future, both in the near term (multimode single fibers or bundles) and far term (single-mode fibers).

The bandwidth of multimode fiber-optic lines is orders of magnitude higher than that of coaxial cable of comparable size and weight. Properly designed couplers, junctions, and terminations should negate the effects of reflection and ringing in fiber-optic lines. The use of opaque jacketing or of an opaque second cladding layer on individual fibers will eliminate EMI and cross talk. Ground shifts cannot occur because of the electrical isolation of terminals provided by fiber optics. Naturally, the general characteristics of fiber optics will be obtained also.

Avionics data-bus systems range up to about 80 m in length. With bandwidths in the 10-MHz region, it is estimated that they could handle some 90% of the present information-transfer requirements. Shipboard systems typically extend to 300 m, and with 300-MHz bandwidths they could handle most of the low-frequency information flow. In both cases, shipping of sensor information (radar, electronic warfare, etc.) extends the bandwidth needs into the 10-GHz-or-higher range. Analysis of proposed data-bus systems with 10 or more terminals indicates that insertion loss at the access coupler is a critical factor and low-loss fiber lines will be required (<100 dB/km on aircraft and <20 dB/km aboard ship).

COST-BENEFIT ANALYSIS

In view of the number of application areas that give increasing importance to fiber- and integrated-optic communications in DoD research and development, it is appropriate to examine the expected benefits of the new technology on as quantitative a basis as possible and to compare the value of the benefits in some meaningful way with expected R&D expenditures.

The purpose of this section is to develop a set of guidelines for performing a cost-benefit analysis for fiber-optic communications technology and to present some preliminary results for specific application areas.

METHOD OF ANALYSIS

The net present value (NPV) method will be used to make a quantitative comparison of alternative strategies for research and development funding. The NPV of a future investment equals the discounted value of benefits minus the discounted value of costs:

$$NPV = \sum_{i=1}^N \frac{b_i - c_i}{(1 + d)^i}$$

where

d = discount rate

b_i = value of benefits in year i

- c_i = value of costs in year i
 N = length of period (in years) for which costs and benefits are computed

For the purpose of this analysis, benefits and costs will be expressed in 1973 dollars. A discount rate of 8% (the official DoD rate of 12% minus a 4% inflation factor) will be assumed. Benefits and costs will be computed for a 20-year period ($N = 20$), beginning with fiscal year 1974. Costs will include expenditures on R&D in (1) components (fiber-optic transmission lines, optical sources, detectors, integrated optical circuits), (2) development of electro-optic modules capable of interfacing with standard equipments, (3) development of suitable packaging techniques for components and modules, (4) writing of MIL-SPECS, and (5) MIL qualification of components and modules. Three different hypothetical R&D investment policies will be compared: (A) high level of effort, \$3.0 million/year for 6 years; (B) low level of effort, \$0.8 million/year for 12 years; and (C) no effort. For each assumed investment policy, benefits will be estimated for each of a number of potential fiber-optic applications. The net present value of benefits will be calculated and compared for each of the policies.

SUMMARY OF PRELIMINARY FINDINGS

Table 3 summarizes the findings of the NPV comparison to date.

TABLE 3. COMPARISON OF NET PRESENT VALUES OF BENEFITS OF HYPOTHETICAL INVESTMENT POLICIES.

Application	Present Value of Benefits, \$ million	
	Policy A	Policy B
Aircraft point-to-point	39	22
Ship point-to-point	2.5	1.5
Aircraft data bus	92	42
Ship data bus	10	5
Towed array	1.6	0.7
Submersible cable (<10 km)	16	7
Submarine hull penetrator	10	6
Total	171	84
Present Value of Costs	13	5.3
Net Present Value of Benefits	158	79

It is emphasized that these figures are of a preliminary nature. Some of the potential applications of fiber-optic communications, such as long-line telecommunications links, stationary array lines, and tactical data and communications links, are not yet included in the calculations of benefits.

because of lack of sufficient data at this time. Also, further efforts to improve the accuracy of the assumptions used in calculating the figures in the table will be carried out.

Table 3 does not reflect the value of benefits of fiber optics which are difficult or impossible to quantify (e.g., security, EMI immunity, fire resistance). In some applications it is probable that such benefits are of more significance than the quantifiable benefits.

CALCULATION OF BENEFITS

It is assumed in the benefit calculations that single-mode and multi-mode fiber-optic transmission lines can be procured at a cost of \$3.00 per meter and that the cost of other components (emitters, detectors, IOCs) can be neglected. These calculations are presented below:

a. Aircraft. It is anticipated that data buses will handle most of the signals transferred in military aircraft of the early 1980s. However, certain wide-bandwidth signals in electronic warfare, weapons control, and control and display subsystems will still be carried by point-to-point links. It is estimated that fiber optics could replace 90 meters of electrical cable per aircraft in point-to-point links, at a savings of 13.5 kgm (30 lb) in weight, and 140 meters of cable in the main data bus, at a savings of 40 kgm (90 lb). The weight penalty is estimated to be \$880 per kgm (\$400 per pound) in procurement costs and \$1300 per kgm (\$600 per pound) in operating and maintenance costs over the life of the aircraft. Based on these figures, the use of fiber optics would save \$30,000 per aircraft for point-to-point links and \$90,000 for the data bus. Using the recent DoD procurement rate of about 330 new aircraft per year, this would mean savings of about \$10 million per year for point-to-point links and \$30 million per year for the data bus.

b. Ships and Submarines. The data bus is also expected to play a major role in the 1980 generation of ships and submarines, with point-to-point links being retained for some high-bandwidth computer and sensor information. Weight savings are not nearly as important for conventional naval vessels as for aircraft. The main savings from using fiber optics for ships and submarines would be in cable procurement and installation costs. For a destroyer, fiber optics could replace 1800 m of the main data bus, at a savings of \$33 per meter, for a total savings of \$400,000 per ship. For point-to-point links, fiber optics could replace 1200 m of electrical cable, at a savings of \$50 per meter. The total savings is \$60,000 per ship for point-to-point links and \$400,000 per ship for the data bus. The figure for submarines is assumed to be 80% of that for the destroyer. Based on a recent procurement rate of seven destroyers and five submarines per year, the total savings are estimated to be \$0.6 million per year for point-to-point links and \$4.4 million per year for the data bus.

c. Towed Array. The cost of a towed array cable for a destroyer is presently \$30,000. However, bandwidth requirements are expected to increase by an order of magnitude in the next 5 years, which would raise the cost of the cable to \$90,000. The use of fiber optics could save \$70,000 per cable. Assuming that each new destroyer is supplied with a towed array and that seven new destroyers are produced per year, the savings due to using fiber optics would be about \$0.5 million per year.

d. Submersible Cable. One DoD communications application requires a high-bandwidth signal to be transmitted over a distance of several kilometers in a submersible cable. The needed bandwidth is unattainable using electrical cable, but is easily within the capability of fiber optics. The value (utility) to DoD of having this capability is estimated at \$5 million per year.

e. Submarine Hull Penetrations. There are about 200 penetrations for bringing electrical signals through the hull of a typical submarine. The use of fiber optics for transmitting the signals through the hull would reduce the size, and therefore the cost, of the hull penetrations. At an estimated savings of \$2500 per hull penetration, the total savings would be \$500,000 per submarine. At a procurement rate of five submarines per year, this adds up to a total savings of \$2.5 million per year.

These guidelines will be applied to each DoD application area in the future as the necessary data are collected and assumptions are examined and improved.

MATERIAL AND DEVICE PHYSICS

Experimental and theoretical work on IOC devices and fabrication techniques has been undertaken at NELC, the University of Washington, UCLA, and Hughes Research Laboratories. The general areas of concentration for each investigator were indicated in the introduction to this report. This section describes the most recent (to 31 March 1973) results at NELC (diffused waveguides, waveguide electro-optic phase modulators, multilayer epitaxial waveguide structures, prototype communication systems), at UCLA (theoretical calculations on waveguides), at the University of Washington (microwave and optical coupling to IOC components), and at HRL (electron beam fabrication techniques for IOCs).

DIFFUSED WAVEGUIDES

The fabrication of waveguides by diffusion has been reported previously (ref 7 and 8). The processing has improved steadily to the point that scattering is no longer detectable from the waveguides. Exact measurement of losses in the diffused waveguides in $\text{Zn}_{1-x}\text{Cd}_x\text{Se}$ and $\text{CdS}_{1-x}\text{Se}_x$ is no longer possible due to the difficulty in obtaining single-crystal ZnSe and CdS commercially in sizes larger than 1 cm. Losses are conservatively estimated to be 2 dB/cm in $\text{Zn}_{1-x}\text{Cd}_x\text{Se}$ using powder diffusant sources, and are prob-

ably under 1 dB/cm. Figure 1 shows the surface of a $\text{Zn}_{0.915}\text{Cd}_{0.085}\text{Se}$ waveguide and an adjacent electrode (see WAVEGUIDE-ELECTRO-OPTIC MODULATORS), taken at $30,000\times$ with a scanning electron microscope (SEM). The object in the guiding area was the only one in a 2-mm length of guide. Absorption losses due to the tail of the absorption edge in $\text{CdS}_{1-x}\text{Se}_x$ will limit guides in this material to about 3 dB/cm at 6328 Å, but at longer wavelengths this loss should be much less. Losses due to the absorption edge in $\text{Zn}_{1-x}\text{Cd}_x\text{Se}$ should be less than 0.5 dB/cm at 6328 Å.

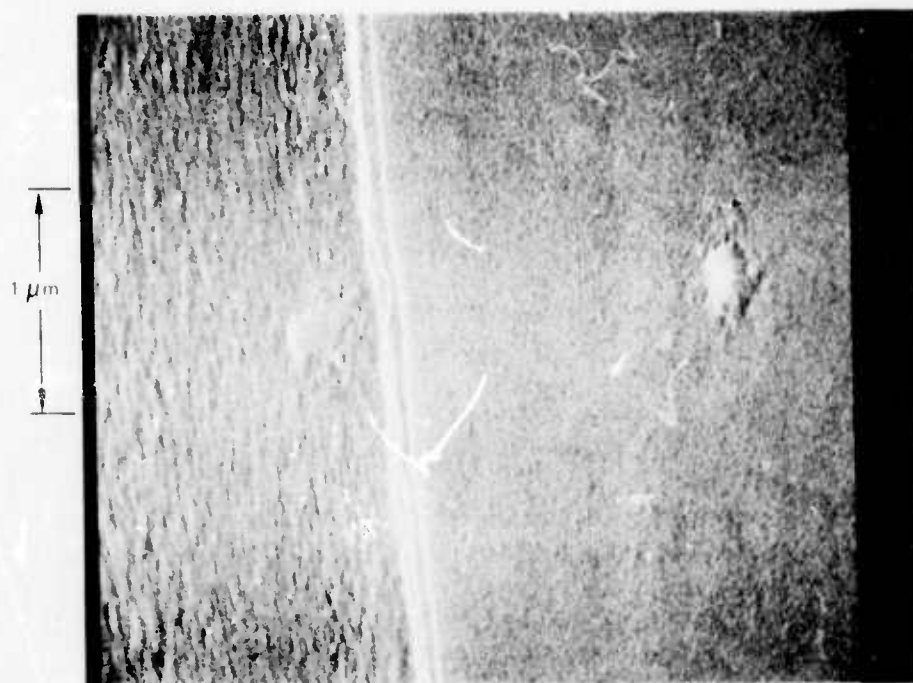


Figure 1. Surface of $\text{Zn}_{0.915}\text{Cd}_{0.085}\text{Se}$ waveguide and adjacent electrode ($30,000\times$)

Conventional photolithography techniques are now being used to produce diffused waveguides. SiO_2 is RF sputtered onto polished substrates, and Shipley AZ-1350 photoresist is used to mask the SiO_2 layer. The photoresist is exposed to ultraviolet (UV) light through a chrome-on-glass mask and then developed. The SiO_2 layer not covered with photoresist is RF-sputter-etched away, leaving the substrate bare for subsequent diffusion. Although optical photolithography cannot approach the quality of electron-beam exposure of photoresist, the index gradient of the diffusion process effectively smooths the pattern edges, giving very-low-loss guides.

Diffusion data on cadmium and selenium diffusion into ZnS, ZnSe, and CdS are not complete. Of the most important systems, Se into CdS and Cd into ZnSe, only the former has been measured (ref 9). Accordingly, experiments were performed to determine the diffusion parameters of cadmium into ZnSe. If data on composition versus refractive index are available or reasonable assumptions can be made about the relationship, then refractive index versus depth can be inferred from composition-versus-depth diffusion data.

Diffusions of cadmium into single-crystal ZnSe were done for various diffusion conditions. The photoluminescence spectrum of the diffused crystal is related to the bandgap or composition at the crystal surface for excitation at short wavelengths. By successively removing material from the surface and measuring spectral positions of emission peaks versus depth into the crystal, one obtains bandgap versus depth (ref 10). Relating bandgap to composition and composition to refractive index, we obtain the index profile.

The "edge" emission band from ZnSe excited with UV light from a 200-W mercury arc was used as the characteristic feature for the emission measurements. Undoped ZnSe exhibits the edge emission peak at 4585 Å. This peak shifts to longer wavelengths as the mole fraction of cadmium increases. The corresponding peak in CdSe occurs at 7060 Å. For small values (<10%) of the mole fraction of cadmium, the bandgap or edge emission is assumed to be linear with composition. The diffused crystal is etched with a bromine-methanol solution and the spectral position of the edge emission redetermined. By measuring how much material was removed by the etch, a composition-versus-depth profile is deduced.

Most of the composition-versus-depth profiles could be best fitted with a complementary error function of form

$$C(x) = C_0 \operatorname{ERFC}(x/A)$$

where x is the depth, C_0 is the surface composition, and A is a constant. Theoretical analysis of diffusion from an inexhaustible source of diffusant gives

$$C(x,t) = C_0 \operatorname{ERFC}(x/2\sqrt{Dt})$$

where D is the diffusion coefficient, a function of temperature, and t is the diffusion time. Some of the profiles at high surface concentrations and large depths could be fitted with several curves, the most common being exponential for a short distance followed by a Gaussian variation. In the worst cases, the error function fit was still quite good, however, so consideration of higher-order diffusion processes is unnecessary for the purpose of interest here. Figure 2 summarizes the diffusion data for a variety of conditions. The variation of D for saturated-cadmium-vapor diffusion is given by

$$D = 6.39 \times 10^{-4} \exp\left(-\frac{1.87 \text{ eV}}{kT}\right)$$

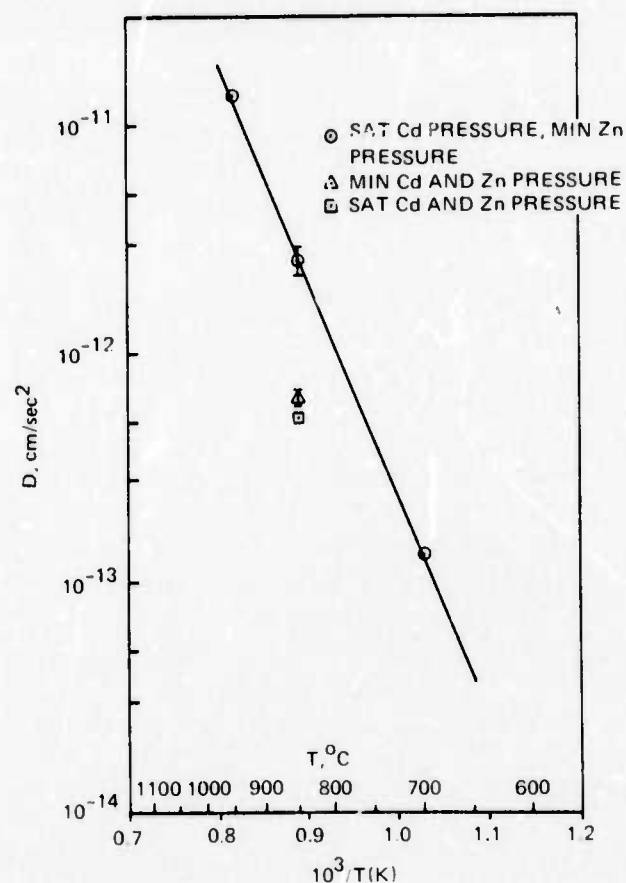


Figure 2. Diffusion of cadmium into ZnSe for various conditions.

in the range 700 to 950°C, where k is the Boltzman constant and T is the temperature

Refractive index versus composition is assumed to vary linearly for small composition changes in ZnSe. Extrapolating the data of Lisitsa et al. (ref 11) on the refractive index of CdSSe, an "effective" refractive index, n , of 2.84 for CdSe at 6328 Å is used. Using this value for CdSe, the refractive index at 6328 Å for $Zn_{1-x}Cd_xSe$ is given by

$$n_x = 2.58 (1 + 0.253x).$$

With n_x a linear function of x , the refractive index profile of a diffused ZnSe crystal is also a complementary error function. Work at NELC (ref 12) indicates that the mode propagation behavior in planar guides with refractive index profiles such as exponential, linear, Gaussian, and complementary error function is not a strong function of the profile shape. As a rule of thumb, the number of modes propagating in an error-function-profile planar

guide of dimension x measured at 20% of surface index value is about the same as the number of modes in the well-known square profile of the same dimension and surface index.

WAVEGUIDE ELECTRO-OPTIC PHASE MODULATORS

The general problem of electro-optic modulation is discussed in reference 13. Electro-optic (EO) modulation in waveguiding regions has been known for many years. A previous NELC report (ref 1) described waveguide EO modulation in planar ZnSe epitaxial layers on GaAs. Figure 3 shows the crystallographic orientation of diffused-waveguide optical modulators (ref 14) in ZnSe and CdS. Two electrode configurations were used to produce two different field operations – electrodes on top of the waveguide (with a low index optical buffer of SiO_2) and the bottom of the substrate (transverse electrodes) and electrodes on each side of the waveguide (parallel electrodes).

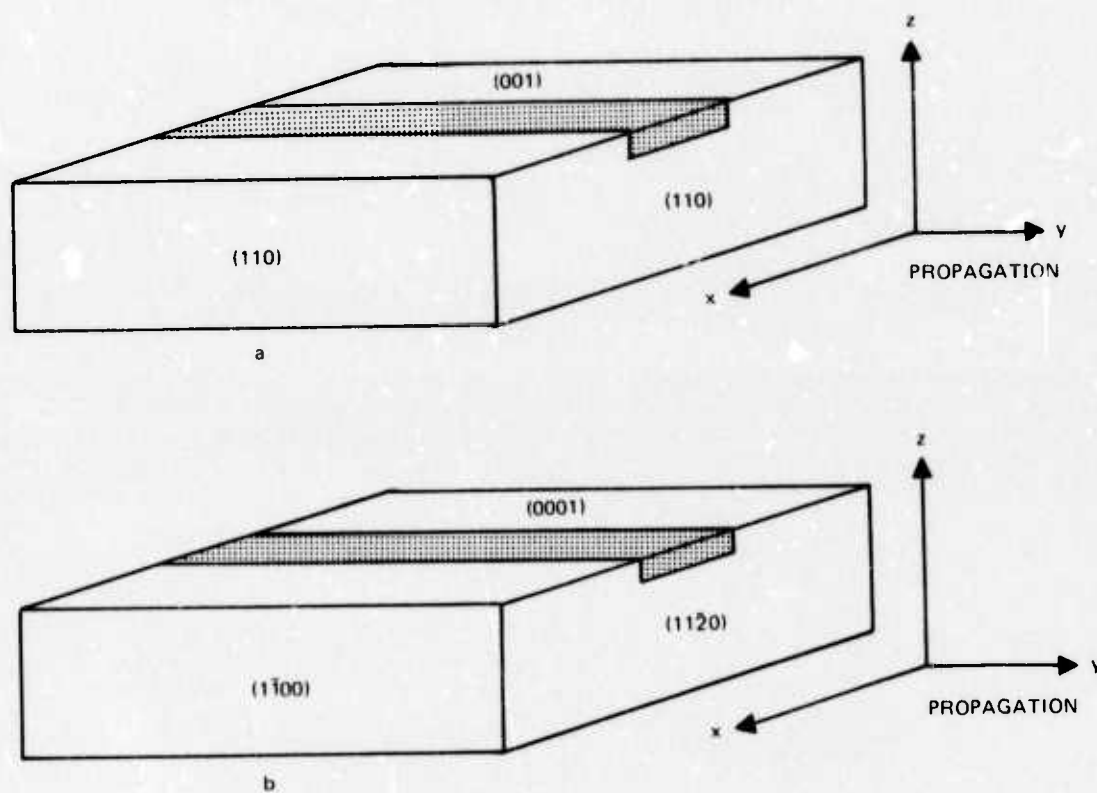


Figure 3. Orientation of diffused-waveguide optical modulators in ZnSe (a.) and CdS (b.).

The polarization phase shift at 6328 Å per applied field for transverse electrodes is (ref 15)

$$\Gamma_{\text{ZnSe}} = \pi(5.4 \times 10^{-5}/\text{volt}) \ell E_z$$

$$\Gamma_{\text{CdS}} = \pi(3.2 \times 10^{-5}/\text{volt}) \ell E_z$$

where E_z is the applied electric field and ℓ is the interaction length. For modulators with parallel electrodes (E in the x direction), the phase shifts become

$$\Gamma_{\text{ZnSe}} = \pi(1.08 \times 10^{-4}/\text{volt}) \ell E_x$$

$$\Gamma_{\text{CdS}} = \pi(1.8 \times 10^{-4}/\text{volt}) \ell E_x.$$

For a given applied voltage, E_z is inversely proportional to modulator thickness. Capacitance also varies as inverse thickness; so large electric fields imply high capacitance for modulators requiring small voltages. Lower capacitance and higher fields are possible with electrodes parallel to and on each side of the waveguide, giving fields in the x direction.

Figure 4 shows a cross section of the parallel-electrode geometry. Using conformal mapping techniques (ref 16 and 17), the field variation in the x direction at $z = 0$ is given by

$$E_x = \frac{bV_0}{K(a/b)} [(x^2 - a^2)(x^2 - b^2)]^{-1/2}$$

where $2V_0$ is the potential difference between the two electrodes and $K(a/b)$ is the complete elliptic integral of the first kind. Field variation in the z direction at $x = 0$ is given by

$$E_z = \frac{bV_0}{K(a/b)} [(z^2 + a^2)(z^2 + b^2)]^{-1/2}$$

Capacitance per unit length of this structure is

$$C = \epsilon \frac{K(a/b)}{K(a/b)}$$

where ϵ is the dielectric permittivity of the medium and $K(a/b) = K[(1-a^2/b^2)^{1/2}]$. For $a/b = 1/3$ (equal electrode width and spacing), with air at $z > 0$ and ZnSe at $z < 0$,

$$C \sim 0.7 \text{ pF/cm}$$

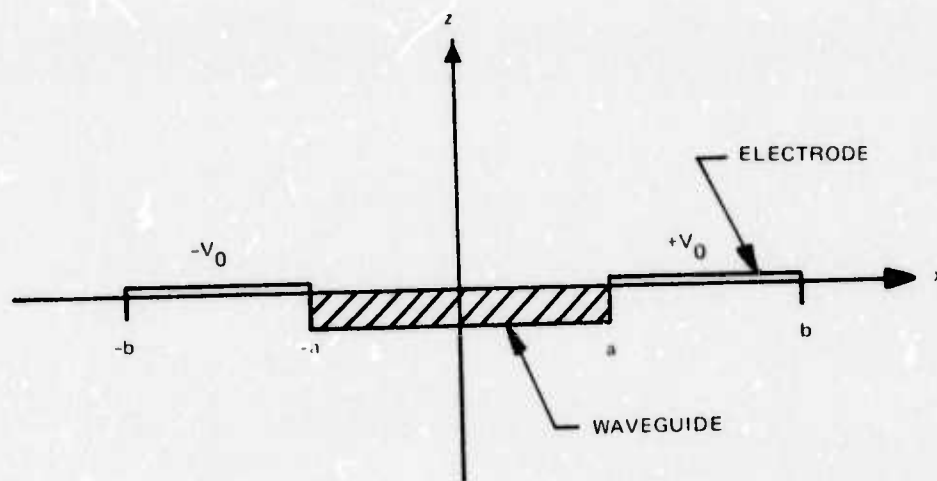


Figure 4. Cross section of parallel-electrode geometry

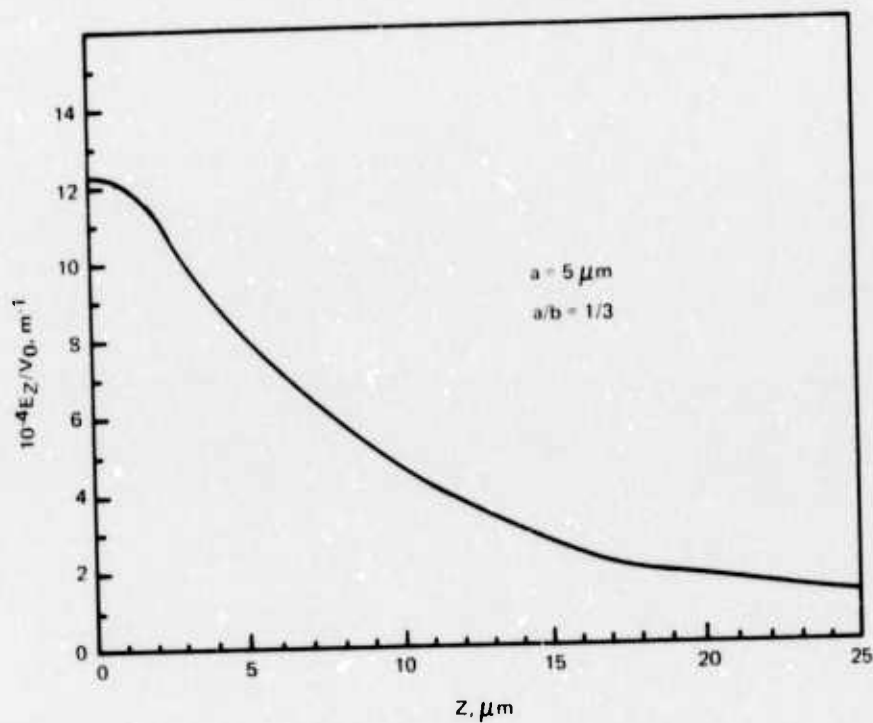


Figure 5. Field variation as a function of z at $x = 0$.

which is very small compared to a parallel-plate capacitor of equivalent geometry. Figures 5, 6 and 7 show field variations for selected geometries and variations in capacitance and field with varying aspect ratio, a/b . Figure 7 indicates that, for highest fields and least capacitance, a/b should be about 0.5. Power requirements for these modulators are determined essentially by the 50-ohm-load resistor used to match generator and cable impedance (see MICROWAVE AND OPTICAL COUPLING TO IOC COMPONENTS).

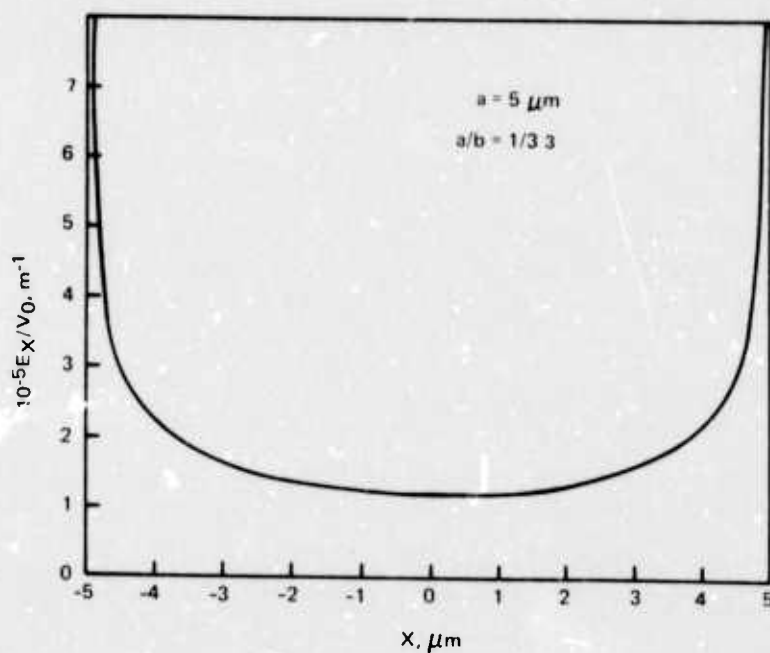


Figure 6. Field variation as a function of x at $z = 0$.

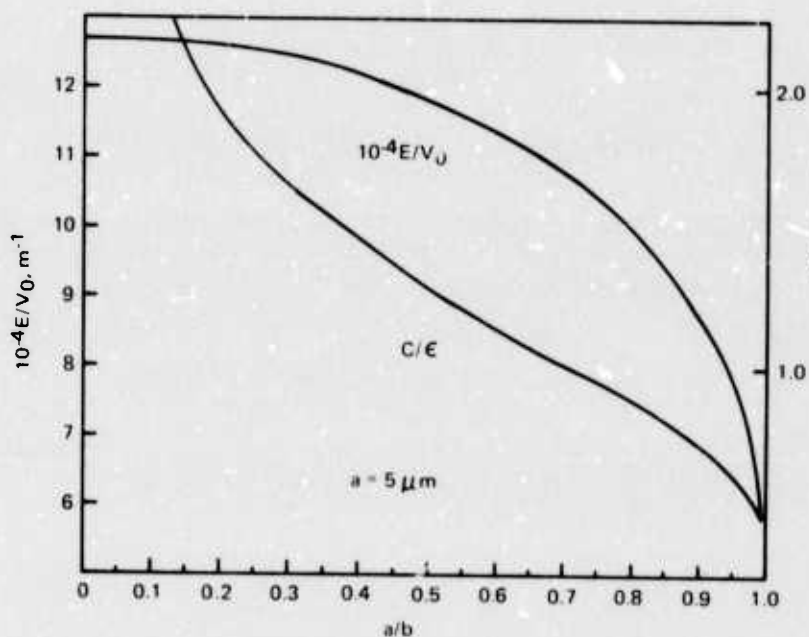


Figure 7. Variations in capacitance and field with varying aspect ratio a/b .

Table 4 summarizes data on several modulators. Figure 8 shows an oscillograph trace of a parallel-electrode modulator. Detector-limited rise times on the order of 1 nsec and cw modulation of 200 MHz have been observed with similar devices. Quantitative measurements of rise times await the acquisition of faster detectors.

TABLE 4. SUMMARY OF MODULATOR DATA.

Sample	Surface Refractive Index, % Δn	Guide Dimensions, μm	Interaction Length, cm	V_{π} , volts	Rise Time (10-90%)
Transverse E field (E \parallel z) diffused waveguides					
$CdS_{0.95}Se_{0.05}$	0.75	1.9 x 19	0.40	145	0.5 μsec
$Zn_{0.915}Cd_{0.085}Se$	0.85	1.6 x 19	0.40	154	50 nsec
$Zn_{0.92}Cd_{0.08}Se$	0.80	1.6 x 19	0.25	68.8	120 nsec
Epitaxy on GaAs (E \parallel z)					
ZnS	----	19 thick	0.30	115	150 nsec
ZnSe	----	10.5 thick	0.25	82.5	150 nsec
Parallel E Field (E \parallel x) diffused waveguides					
$CdS_{0.95}Se_{0.05}$	0.75	1.9 x 19	0.25	37.2	12 μsec
$Zn_{0.915}Cd_{0.085}Se$	0.85	1.6 x 19	0.22	72.0	<5 nsec

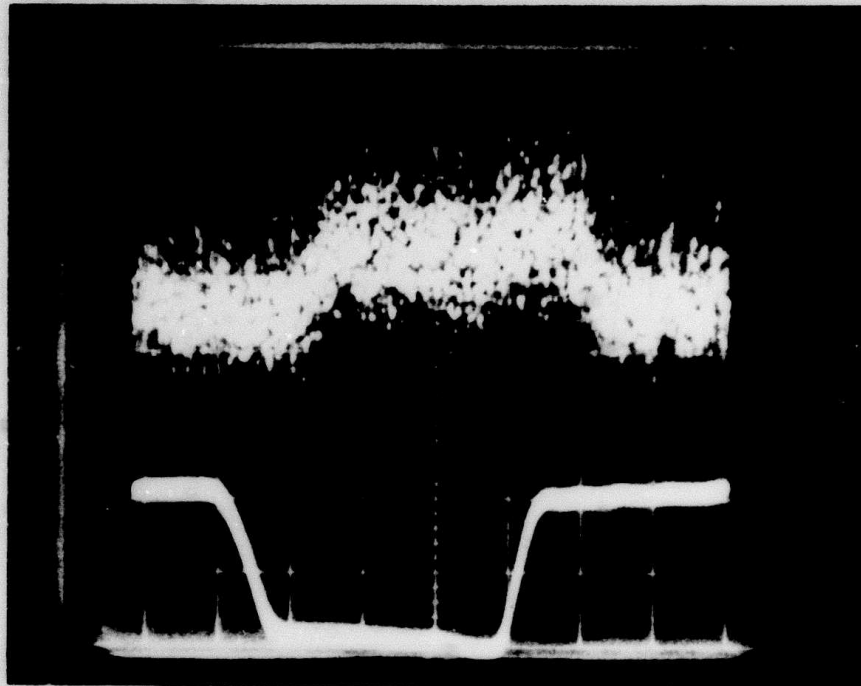


Figure 8. Oscilloscope of modulator performance. Top trace is light output; bottom trace is drive voltage, 25 V/DIV. Horizontal scale is 20 nsec/DIV.

MULTILAYER EPITAXIAL WAVEGUIDE STRUCTURES

The previous report (ref 1) of work under this program described proposed multilayer epitaxial layers of ZnSeTe and ZnCdSe on ZnSe on a GaAs substrate as promising structures. Delivery has been taken on both systems from Photoelectronic Materials Corporation, and preliminary data indicate that extremely low-loss guiding is obtained. Subsequent waveguide fabrication techniques (the structures themselves are excellent planar waveguides) to produce defined geometries are not completely established; however, ion machining and diffusion doping are excellent candidates.

THEORETICAL CALCULATIONS ON WAVEGUIDES

The problem of propagation in nonuniform waveguides is currently being addressed. The most recent work (ref 18) involves analysis of the waveguiding properties of three types of periodic structures in waveguides which may have important applications as frequency-selective couplers, filters, and distributed feedback lasers and in phase-matching-waveguide nonlinear processes.

General solutions to the wave equation are derived in the case of periodically varying media, where

$$\epsilon(z) = \epsilon_1 [1 + \eta f(Kz)]$$

The dielectric permittivity is expressed in terms of the constants η and k and $f(\xi)$, a periodic function. The solutions involve summations of space harmonics in Floquet form and Fourier decomposition of the permittivity. Three cases are of interest:

1. Longitudinally inhomogeneous thin-film waveguide. In this type of periodic waveguide, the permittivity varies as

$$\epsilon(z) = \epsilon_1 [1 + \eta \cos(Kz)]$$

with the waveguide imbedded in a region of lower permittivity, ϵ_2 , as in figure 9a.

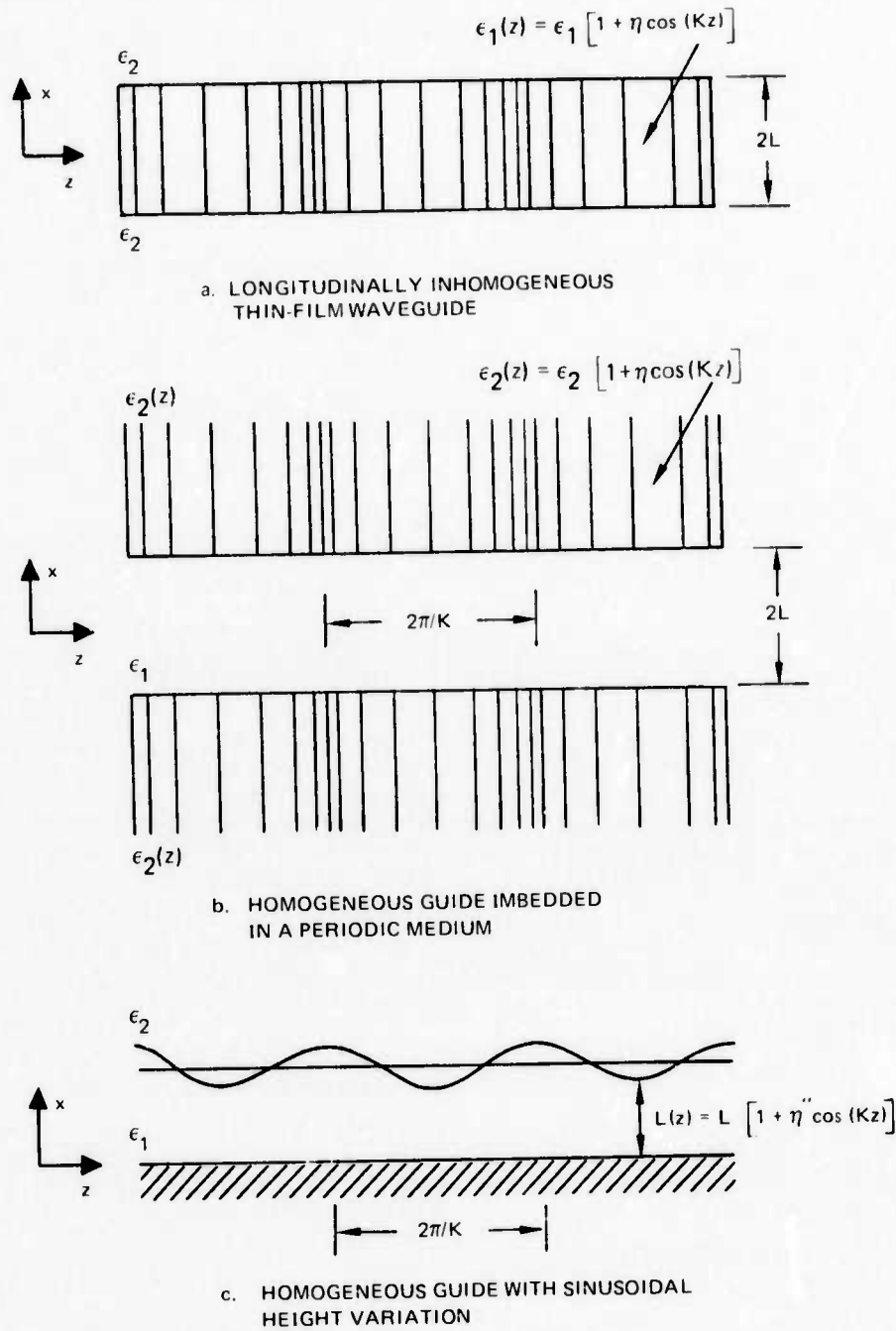


Figure 9. Several configurations for theoretical waveguide calculations.

2. Homogeneous guide imbedded in a periodic medium. In this configuration, the dielectric surrounding the waveguide contains longitudinally periodic variations in permittivity, as in figure 9b.

$$\epsilon_2(z) = \epsilon_2 [1 + \eta \cos(Kz)]$$

3. Homogeneous guide with sinusoidal height variation. In this configuration, a periodic variation in the guide height is considered, as in figure 9c.

$$L(z) = L[1 + \eta \cos(Kz)]$$

Permanent periodic structures can be formed in a large variety of ways, including machining, ion implantation, diffusion doping and photopolymerization. Dynamic periodic variations in permittivity can be accomplished with electro-, magneto-, and acousto-optical techniques. Devices employing periodic structures include distributed feedback lasers, grating couplers, and acousto-, magneto-, and electro-optic modulators. An area of interest in using periodic structures is for phase matching in nonlinear interactions, with applications in up conversion, second-harmonic generation, and parametric oscillators.

An important application of immediate interest is the frequency-selective coupler. The use of a distributed, periodic coupling structure between two waveguides allows the selection of a particular frequency (wavelength) even if the guide can carry a large number of different frequencies. Proper selection of device parameters may allow coupling at several selected frequencies and, if the periodic structure is of the dynamic type, variable-frequency filters are possible. The same techniques can be extended to the construction of waveguide filters in which a particular frequency can be attenuated strongly in a short distance.

MICROWAVE AND OPTICAL COUPLING TO IOC COMPONENTS

The problem of coupling microwave and optical power most efficiently into IOC components is being studied. As an example of typical device characteristics to be considered, an optical-waveguide diffraction modulator was analyzed in terms of parameters that affect ultimate overall performance. Thin-film liquid-waveguide diffraction modulators with interdigital electrodes (ref 19 and 20) are representative of a large class of IOC devices which require optimization with respect to performance. A complete treatment of these considerations is found in reference 21.

Figure 10 shows a cross section of the modulator configuration. The electric field within the waveguide is found to be approximately

$$E_o \simeq A_o' (\exp -\pi z/2a) \left[\sin\left(\frac{\pi y}{2a}\right) - \cos\left(\frac{\pi y}{2a}\right) \right]$$

with

$$\frac{A_o'}{A_o} = 2 / \left[\left(1 + \frac{\epsilon_2}{\epsilon_1}\right) \exp\left(\frac{\pi t}{2a}\right) + \left(1 - \frac{\epsilon_2}{\epsilon_1}\right) \exp\left(-\frac{\pi t}{2a}\right) \right]$$

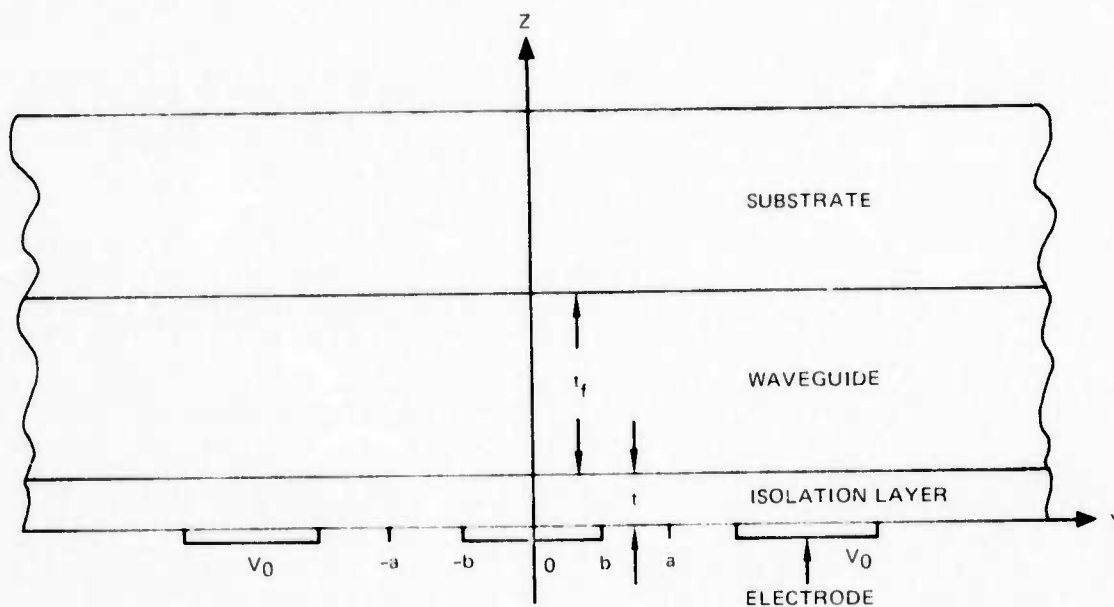


Figure 10. Cross section of optical liquid-waveguide diffraction modulator.

$$\frac{A_0}{V_0/2a} \approx 2 \left\{ \sin\left(\frac{\pi p}{2}\right) - p + (1-p^2)^{1/2} \left[1 - \sin\left(\frac{\pi p}{2}\right) / \cos(h^{-1}p^{-1}) \right] \right\} / (1-p); \quad p = \frac{a}{b}$$

A'_0/A_0 represents a loss in the field strength because of the isolation layer. ϵ_1 and ϵ_2 are the dielectric permittivities of the isolation layer (SiO_2) and the waveguide layer (nitrobenzene), respectively. A'/A_0 is on the order of 1.

At electrical modulation wavelengths that are larger than the device dimensions, the modulator can be modeled as a discrete-component circuit. Figure 11 shows the equivalent circuit used for the calculations. C_a, C_b, C_c, C_d are calculated in reference 21 for this modulator configuration. With losses present in the dielectrics forming the modulator, a conductance, G_d , must be introduced which relates to the loss tangent of waveguide dielectric:

$$G_d = \frac{\sigma}{\epsilon_2} C_d = w \frac{\epsilon_2''}{\epsilon_2'} C_d = \tan \delta C_d$$

where σ and $\tan \delta$ are the conductivity and dielectric loss tangent, respectively. For most semiconductor or crystal electro-optic modulators, $\tan \delta$

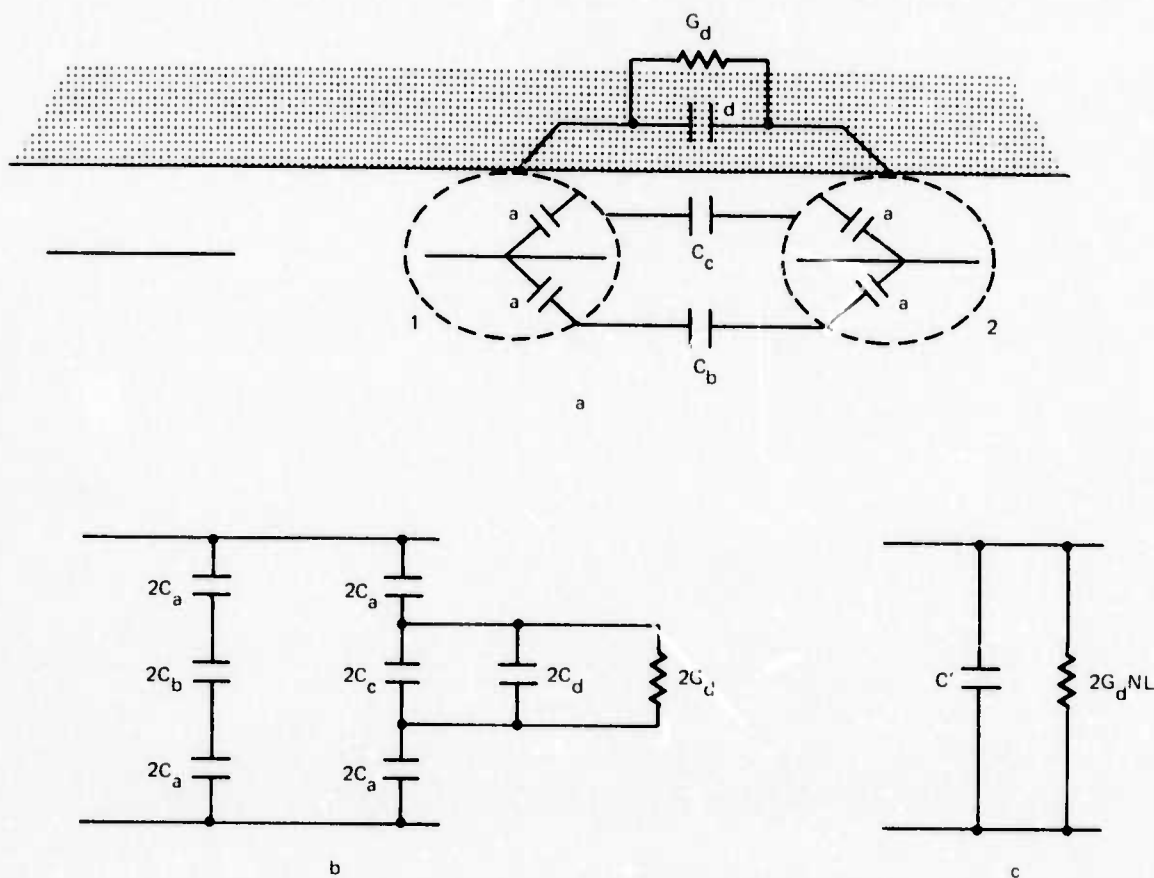


Figure 11. Optical-waveguide diffraction modulator modeled as three discrete-component circuits.

is very small. The low-frequency cutoff of this modulator configuration is found to be

$$f_{\text{LFC}} = \frac{G_d}{\pi C_a} = \frac{\sigma}{\epsilon_2} \frac{C_d}{\pi C_a}$$

The high-frequency cutoff is found from considering termination of the voltage driver in its characteristic impedance (R_s) to avoid reflected power (fig. 12a and 12c):

$$f_{\text{HFC}} = \frac{1}{2\pi R_s C'}$$

A modulator with external circuitry for resonant tuning at a frequency f_0 (fig. 12b and 12d) has bandwidth

$$\frac{BW}{f_0} = BW \frac{\sqrt{LC'}}{2\pi} = 2\pi f_0 R_s C'$$

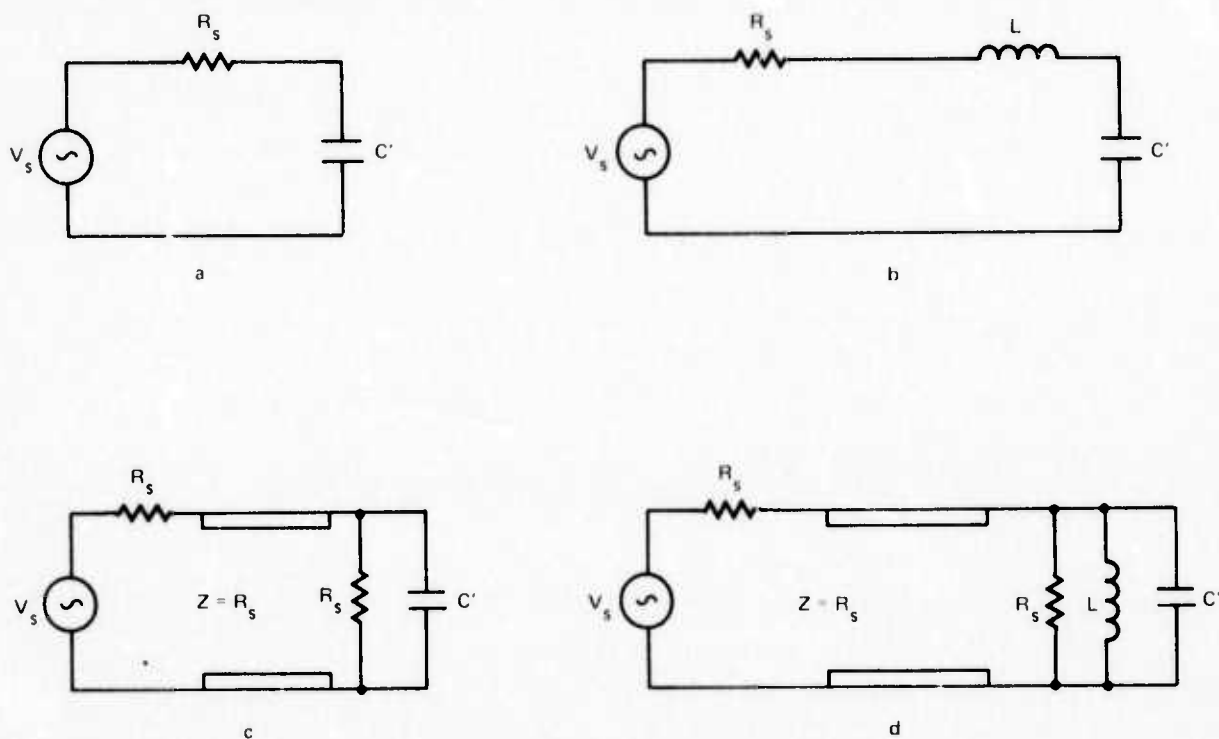


Figure 12. Modulator lumped-parameter circuits for: modulator only (a.), resonant tuning (b.), modulator with a transmission line of characteristic impedance $Z = R_s$ (c.), and resonant tuning with a transmission line (d.).

As might be expected, the magnitude of C' is most important for high-frequency performance. With short electrodes, a small number of electrode pairs and moderate electrode-spacing capacitances on the order of picofarads may be achieved. For systems with $R_s = 50 \Omega$, 3-GHz modulation is possible in principle. Capacitances on the order of 0.5 pF/mm per electrode pair are typical of the interdigital electrode modulators studied here. For comparison of various devices, the figure of merit is used with the lumped-component circuit of figure 11a. The figure of merit is the ratio of the power dissipated in R_s at cutoff to the cutoff frequency, f_c :

$$P_{R_s} = \frac{1}{2} V_p^2 / R_s = \frac{1}{2} (2\pi f)^2 (C')^2 R_s V_p^2$$

Expressing R_s in terms of the bandwidth,

$$\frac{P_{R_s}}{f_c} = \frac{P_{R_s}}{BW} = \pi C' V_p^2$$

If V_p is taken as the voltage required for 100% modulation, the figure of merit becomes

$$\frac{P_{R_s}}{BW} = \pi \left(\frac{C'}{nL} \right) \frac{Wa}{\left(\frac{2a}{\pi t_f} \right) \left(\frac{A_O}{A_O} \right)^2 \left(\frac{A_O}{v/2a} \right)^2 K}$$

where W is the device width, $W = 4aN$ (where N is the number of electrode pairs); L is the electrode length; and K is the Kerr constant for the nitrobenzene waveguide. As an approximation using $\left(\frac{C'}{NL} \right) = 0.2$ pF/mm, the figure of merit is on the order of

$$\frac{P_{R_s}}{BW} \sim 0.100 W/2a$$

If $2a \sim 1 \mu\text{m}$, the figure of merit is on the order of $(10^5 W)$ watts/GHz. When the modulator width W is on the order of a few micrometers, less than 1 watt/GHz of power is required.

Electrical coupling of microwave energy into modulator structures may be done quite efficiently with slotted transmission lines or strip-line technology. Careful matching of impedances will be necessary for optimum microwave coupling to these devices.

ELECTRON-BEAM FABRICATION TECHNIQUES FOR IOCs

It is well known that conventional photolithographic techniques do not possess the inherent edge smoothness and resolution necessary for ultimate fabrication of IOC components. Some fabrication techniques, such as diffusion described earlier in this report, can use conventional photolithography for establishing large patterns. Regardless of process, however, the extremely small dimensions and close tolerances required for devices such as waveguide couplers make a controllable fabrication technique, such as scanning-electron-microscope exposure of a resist material, the process of choice.

The SEM microfabrication facility at Hughes Research Laboratories is known for a high-resolution pattern-generation capability. Under contract to NELC (ref 22), HRL is engaged in the development of techniques suitable for high-resolution fabrication of patterns for IOC components. Figure 13 shows some possible fabrication processes.

Several techniques that show promise were used to fabricate potential waveguiding and/or masking structures in polymers. Direct SEM exposure without development in polymethyl methacrylate (PMM) produced changes in the resist film which can be associated with refractive

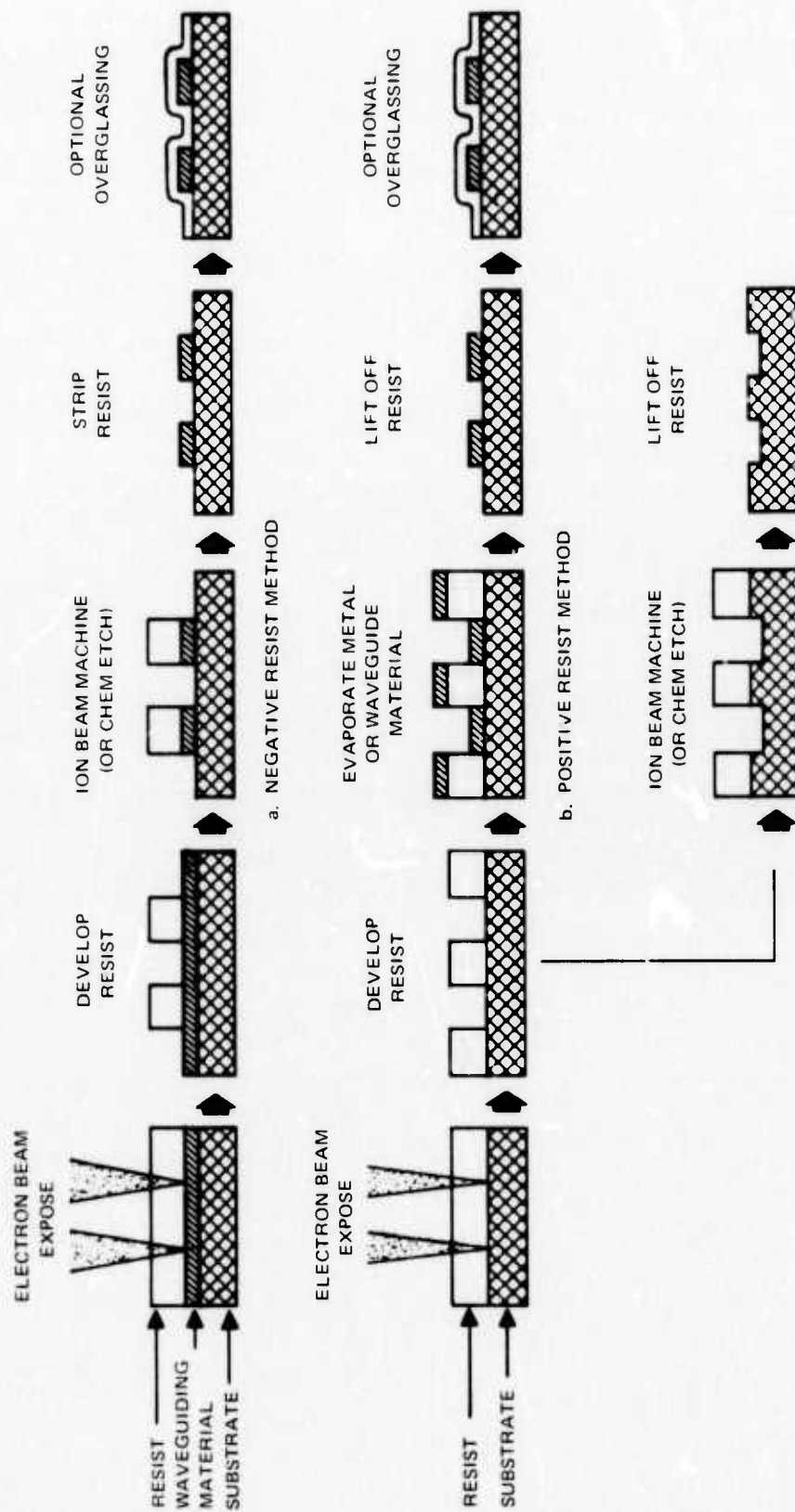


Figure 1.3. Two possible high-resolution IOC-component fabrication processes.

index changes. Development of the exposed resist produces ridges of PMM which can be used to guide light with no further processing. Figure 14 shows some typical PMM patterns fabricated on SiO_2 layers with silicon substrates. A focused beam from a He-Ne laser was used to excite the $1\text{-}\mu\text{m}$ -high waveguides, and guiding was observed in these structures by scattered light in the polymer. Apparent in figure 13 is the extreme edge smoothness possible with the SEM technique.

SiO_2 was RF sputtered and chemical-vapor deposited (CVD) on silicon substrates, then either chemically etched or ion-beam machined, using SEM-exposed PMM. Figure 15 shows chemically etched, CVD SiO_2 on silicon. A lift-off technique was also used with RF-sputtered 705% glass films on thermally grown SiO_2 on silicon substrates, but this technique produced quite severe edge roughness.

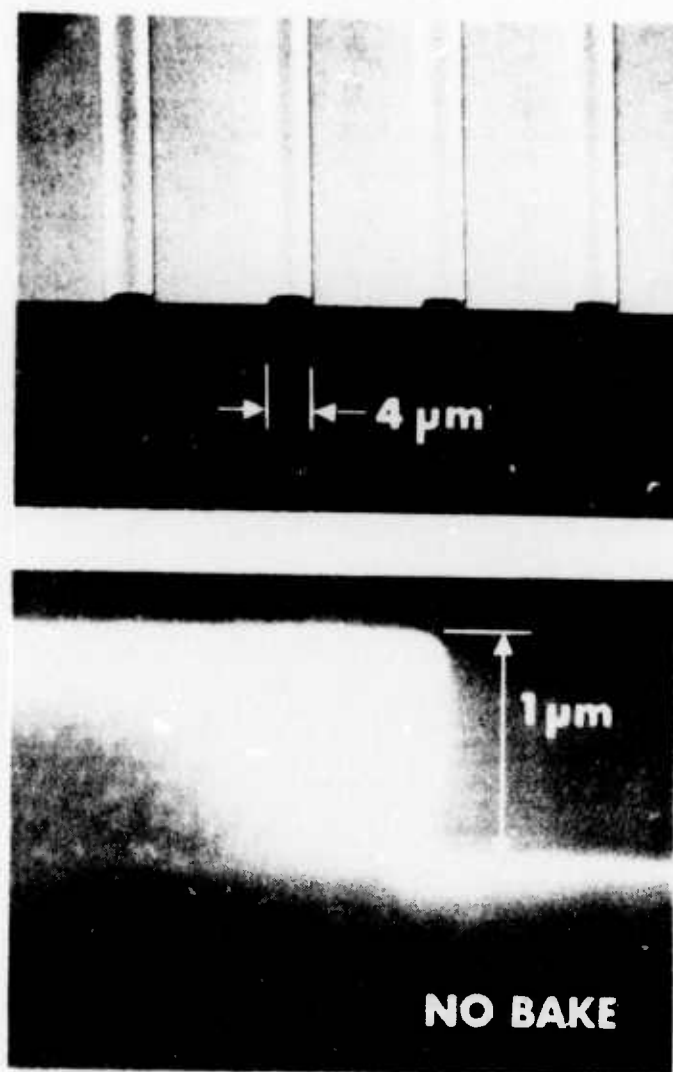


Figure 14. Typical PMM pattern fabricated on SiO_2 layers with silicon substrates.

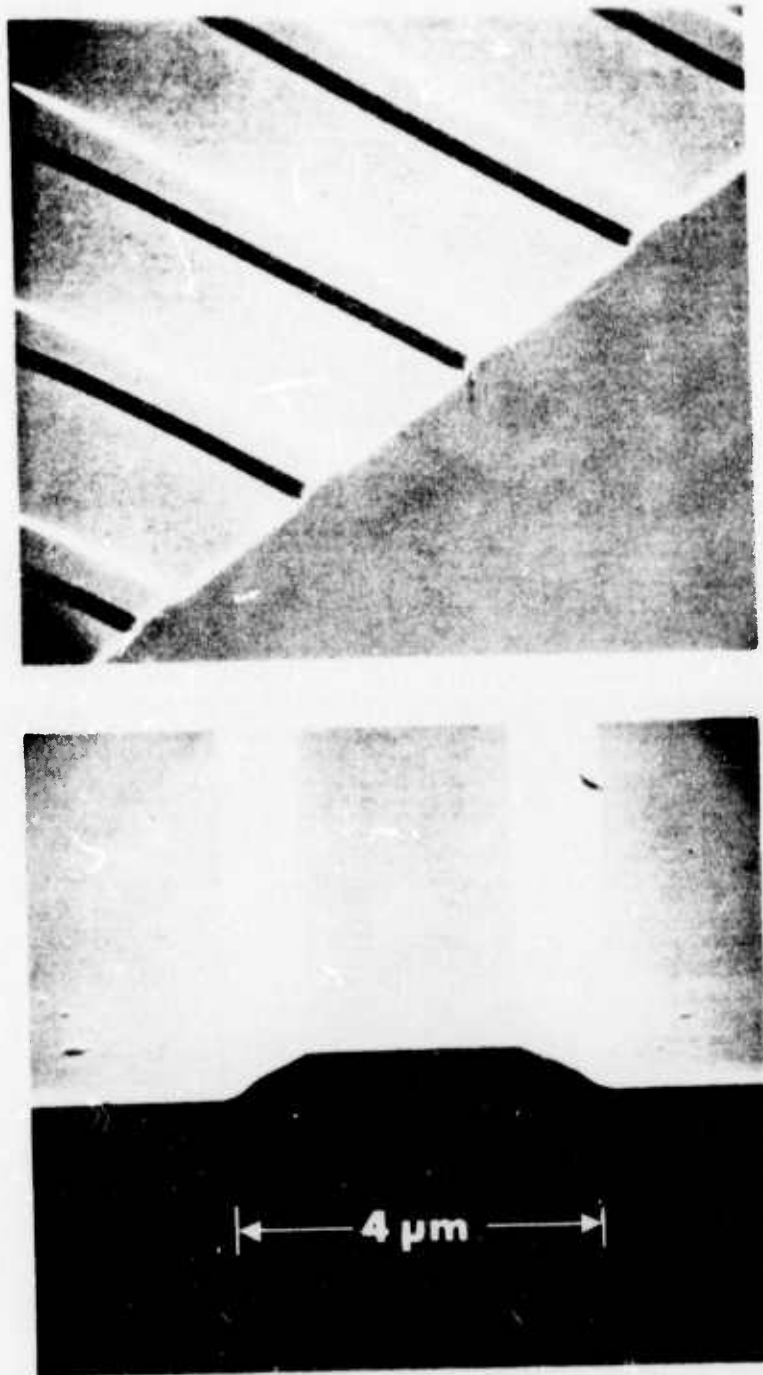


Figure 15. Chemically etched, chemical-vapor-deposited SiO_2 on silicon

A very promising technique is resist replacement. In this process, the exposed and developed resist pattern is used in a lift-off technique to leave on the substrate a material with superior resistance to ion-beam micro-machining. Aluminum can be used as well as manganese metal films, which show greater resistance to the ion beam.

PMM is the most common resist for SEM exposure, but several other polymers are candidates that show qualities which may be superior for some applications. Polyglycidyl methacrylate (PGM), epoxidized polybutadiene (EPB), polyvinyl siloxane (PVS), and polyphenyl siloxane (PPS) are being considered as possible replacements in PMM applications for which PMM is not well suited.

PROTOTYPE COMMUNICATION SYSTEMS

To provide guidance to the program and to characterize, evaluate, and demonstrate the components and their performance, three guided-wave optic breadboard systems have been projected. These prototype systems are described in table 5, and the ascending capabilities and types of components required are presented. These systems were chosen to exemplify representative DoD communications needs and provide the basis for advanced and engineering development phases of component and system development.

TABLE 5. PROTOTYPE IOC COMMUNICATION SYSTEMS.

	SYSTEM		
	1	2	3
Component Configuration	Discrete	Hybrid	Hybrid/integrated
Type of Link	Point-to-point	+ Repeater	Data bus (FDM)
Bandwidth	500 MHz	1 GHz	5 GHz
Elements	Source — 1 wavelength	→ X	Many wavelengths
	Modulator	→ X	→ X
	Detector	→ X	→ X
		IOC-fiber coupler	→ X
		Multipole switch	→ X
			Frequency selective coupler
Estimated Completion Date	Fiber waveguide		
	Multimode	Single mode	→ X
	Jan 74	Jun 75	Jun 76

SUMMARY

Fiber optics will offer major benefits to military communications in the near term, with discrete-component, multimode-fiber systems, and in the future, with IOC's and single-mode-fiber systems. The important properties of these systems will include:

1. EMI immunity
2. Security — no signal leakage
3. Large bandwidth
4. Small size and light weight

Consideration of applications assessment indicates that avionics data transfer is likely to be the first area that will benefit from fiber-optic technology. Definite decreases in initial cost and weight are obtainable using fiber-optic transmission lines. General applications areas are:

1. Avionics, properties 1 to 4 above, for lower-cost point-to-point systems.
2. Shipboard applications, properties 1 to 4 above, for lower-cost point-to-point systems.
3. Undersea applications, providing small, lightweight, wide-bandwidth data channels in cables for arrays, tethers, and long point-to-point links.
4. Land-based applications, which include system weight reductions in mobile command control systems and secure, wide-bandwidth landlines.
5. Data bus applications, which, using fiber-optic transmission lines, couplers, and switches, promise to have wide impact in avionics, high-performance surface craft, and shipboard systems performance.

A cost-benefit was begun and analysis indicates potential savings of several million dollars in several applications areas from R&D investments in fiber-optic technology. The areas of potentially largest savings thus far are the aircraft data-bus concept, aircraft point-to-point links, undersea cables, shipboard data-bus systems, and submarine hull penetrations. Preliminary analysis using the net-present-value method indicates a potential savings of more than \$150 million over a 20-year period if fiber-optic technology is utilized in the above areas.

Integrated optical circuits will be necessary to provide efficient coupling, switching, and frequency-division multiplexing and to utilize the full bandwidth and the data bus capabilities of the fiber-optic transmission lines. The material and device physics necessary to fabricate IOC elements have progressed rapidly in recent months. Some highlights of the program include:

1. Diffusion parameters have been improved to produce low-loss waveguides in ZnSe and CdS using conventional photoresist technology.
2. Ultrafast waveguide electro-optic modulation in ZnSe and CdS has been demonstrated. Devices with optical pulse rise times of less than 5 nsec have been fabricated which require less than 40 volts for operation.

3. Multilayer heteroepitaxial films of ZnCdSe and ZnSeTe on GaAs substrates have been acquired for study as optically active waveguides and device substrates.

4. Theoretical calculations have been made for a variety of periodically varying dielectric-coefficient geometries. Several promising structures and devices using periodic variation are being studied.

5. The coupling of microwave and optical signals into IOC components has been explored using an electro-optic modulator structure that is representative of typical devices encountered. Figure-of-merit calculations indicate that power requirements for various device parameters are very low.

6. Electron-beam exposure of resist materials and subsequent fabrication has been used to demonstrate fabrication capability and to construct waveguides with excellent edge quality in polymethyl methacrylate and SiO_2 .

7. Prototype communications systems employing discrete components, fiber optics, and eventually IOC components have been proposed as demonstration and test-bed optical links for the communication systems of the future.

In conclusion, fiber-optic and IOC technologies are advancing rapidly. Even as this report is being written, improvements and developments on fiber-optic and IOC devices and components are rapidly bringing the level of technology to that of the realizable systems required for a wide variety of DoD tasks.

REFERENCES

1. Naval Electronics Laboratory Center Technical Report 1861, Integrated Optics, by D. B. Hall, 30 January 1973
2. Naval Electronics Laboratory Center Technical Report 1763, Transfer of Information on Naval Vessels via Fiber Optics Transmission Lines, by H. F. Taylor, 3 May 1971
3. Taylor, H. F., "Fiber Optics Communications," Naval Research Reviews, January 1973
4. Naval Electronics Laboratory Center Technical Report 1846, Integrated Optics in Avionics Systems, by J. F. Poulson, T. P. Lindgren, and H. F. Taylor, Volume 1, 8 November 1972
5. Spero, J. R., Hicks, W. F., and Greene, P. L., "A Philosophy of Naval Ship Design and Construction," Naval Ship Systems Command Technical News, v. 21, p. 2, December 1972
6. "Electrical Multiplexing to Control B-1 Bomber," Electronic Design Magazine, 6 January 1972
7. Taylor, H. F., Martin, W. E., Hall, D. B., and Smiley, V. N., "Fabrication of Single-Crystal Semiconductor Optical Waveguides by Solid State Diffusion," Applied Physics Letters, v. 21, p. 95, 1972
8. Martin, W. E., and Hall, D. B., "Optical Waveguides by Diffusion in II-VI Compounds," Applied Physics Letters, v. 21, p. 325, 1972
9. Woodbury, H. H., and Hall, R. B., "Diffusion of the Chalcogens in the II-VI Compounds," Physical Review, v. 157, p. 641, 1967
10. Martin, W. E., "Photoluminescence Determinations of Cd Diffusion in ZnSe," Journal of Applied Physics, December 1973
11. Lisitsa, M. P., Gudymenko, L. F., Malinko, V. N., and Terekhova, S. F., "Dispersion of the Refractive Indices and Birefringence of $\text{CdS}_x\text{Se}_{1-x}$ Single Crystals," Physica Status Solidi, v. 31, p. 389, 1969
12. Caton, W. M., to be published
13. Yariv, A., Quantum Electronics, Wiley, 1967
14. Martin, W. E., "Waveguide Electro-Optic Modulation in II-VI Compounds," Journal of Applied Physics, August 1973
15. Kaminow, I. P., and Turner, E. H., "Electrooptic Light Modulators," Proceedings of the IEEE, v. 54, p. 1374, 1966
16. Kober, H., Dictionary of Conformal Representation, Dover, 1957
17. Mathews, J., and Walker, R. L., Mathematical Methods of Physics, Benjamin, 1965
18. Elachi, C., and Yeh, C., Journal of Applied Physics, to be published
19. GiaRusso, D. P., and Harris, J. H., "Electrooptic Modulation in a Thin Film Waveguide," Applied Optics, v. 10, p. 2787, 1971

20. Polky, J. N., and Harris, J. H., "Interdigital Electro-optic Thin-Film Modulator," Applied Physics Letters, v. 21, p. 307, 1972
21. University of Washington, Contract N00953-73-M-0250, Final Report, Theoretical Analysis of Microwave Coupling in an Electrooptic Diffraction Modulation, by R. B. Smith and J. H. Harris, December 1972
22. Hughes Research Laboratories, Contract N00123-73-C-0231, Final Report, Beam Techniques for the Fabrication of Integrated Optical Circuits, by E. D. Wolf, H. L. Garvin, and R. G. Wilson, March 1973